NOAA Technical Memorandum
NESDIS AISC 14

ICE COVER ON CHESAPEAKE BAY FROM AVHRR AND LANDSAT IMAGERY, WINTER OF 1987-88

Michael J. Dowgiallo
Martin C. Predoehl
Richard P. Stumpf

Washington, D.C.
June 1988

U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Environmental Satellite, Data, and Information Service

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LIST OF ABBREVIATIONS AND ACRONYMS

AISC	Assessment and Information Services Center
AVHRR	Advanced Very High Resolution Radiometer
BWI	Baltimore-Washington International Airport
^{o}C	degrees Celsius
Deg	degree
E_0	solar irradiance
EOSAT	Earth Observation Satellite Company
^{o}F	degrees Fahrenheit
FDD	Freezing Degree-Day
GIS	Geographical Information System
GOES	Geostationary Operational Environmental Satellite
θ_0	zenith angle of the sun
k	ice thickness reduction coefficient
K_i	coefficient of thermal conductivity of ice
km	kilometer(s)
L_*	radiance measured at the satellite
L_A	atmospheric path radiance
L_i	latent heat of fusion
Landsat	Land satellite
LFM	Limited-area, Fine-mesh Model
m	meter(s)
mi	mile(s)
MRF	Medium Range Forecast
MSS	Multispectral Scanner
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
NTIS	National Technical Information Service
NWS	National Weather Service
pixel	picture element
R	reflectance
ρ_i	density of ice
sq	square
T(AVG)	average temperature for the day
TIROS	Television and Infrared Observing Satellite
TM	Thematic Mapper

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Michael J. Dowgiallo, Martin C. Predoehl, and Richard P. Stumpf

Marine Environmental Assessment Division
Assessment and Information Services Center
National Environmental Satellite, Data, and
Information Service, Washington, DC 20235

ABSTRACT. Ice cover on Chesapeake Bay during winter 1987-88 was analyzed using two types of satellite imagery and ice reconnaissance data from the U. S. Coast Guard. Multispectral Scanner (MSS) data from Landsat and Advanced Very High Resolution Radiometer (AVHRR) data from the NOAA TIROS-N polar-orbiting satellites were compared for usefulness in detection and evaluation of ice on Chesapeake Bay. Decreases in air temperatures and surface water temperatures in the upper Bay are quantitatively linked to ice formation. Dates of maximum ice cover were identified from accumulated freezing degree-days and from computed and actual 1987-88 ice cover. Ice conditions during 1987-88, a near-normal winter in the Bay area, were compared to conditions in winter 1981-82, a much colder winter with more ice. Maximum ice cover was 14 percent during winter 1987-88 and 34 percent during winter 1981-82.

1. INTRODUCTION

During the last three decades, satellites have provided a convenient means to obtain synoptic ice data. The satellite imagery has provided important data on ice cover and ice edge locations over large areas such as the Great Lakes, the Arctic, and Antarctica. Several satellites have provided the imagery, including the Geostationary Operational Environmental Satellite (GOES), NOAA TIROS-N polar-orbiting satellites, and Landsat.

Landsat imagery has been used successfully to detect ice in smaller bays and rivers because of its high resolution (less than 80 m). Foster (1980), in his study of Chesapeake Bay ice during the unusually cold winters of 1976-77, 1977-78, and 1978-79, demonstrated Landsat's capabilities for monitoring ice growth and decay, for detecting ice motions, and for measuring ice extent.

Some work has been done using lower-resolution GOES and polar-orbiting satellite imagery to monitor ice in small areas such as rivers (McGinnis and Schneider, 1978), though these studies are rare. The 1 km resolution of the NOAA Advanced Very High Resolution Radiometer (AVHRR) onboard the TIROS-N satellite previously discouraged investigators from using this imagery extensively to study ice in Chesapeake Bay. However, recent work on turbidity (Stumpf, 1987) and water temperature (Everdale, 1985) in Chesapeake Bay has shown that the 1 km spatial resolution of the AVHRR sensor is a disadvantage only when considering fine-scale features or small estuaries, i.e., those less than about 4 km across. The routine daily coverage of the AVHRR data offers a temporal advantage in the study of ice compared to Landsat imagery which is available every 16 days.

Everdale (1985) described how the delineation of ice within estuaries using the AVHRR data can be performed using visible channel 1 data. By masking the land in an AVHRR ice image using an overlay, he showed it is possible to clearly delineate ice within Chesapeake Bay. In the present study, we will compare imagery from the high-resolution Landsat data with the imagery from the lower-resolution AVHRR data using the land mask overlay technique.

The amount of ice on Chesapeake Bay is a complex function of temperature, salinity, wind, precipitation and streamflow, and the shape, total water volume, and surface area of the Bay (Figure 1) (Foster, 1980). Many of the previous studies in the colder regions of the world and in Chesapeake Bay have used an integrated approach in the study of ice cover, analyzing environmental parameters such as air and water temperatures, along with ice observation data (visual aerial reconnaissance, airborne radar, satellite imagery) to delineate ice features and coverage. We take a similar approach in this study of Chesapeake Bay ice cover by using, in addition to the two types of satellite imagery, U. S. Coast Guard ice reconnaissance data, air and water temperatures, and an analysis of freezing degree-days.

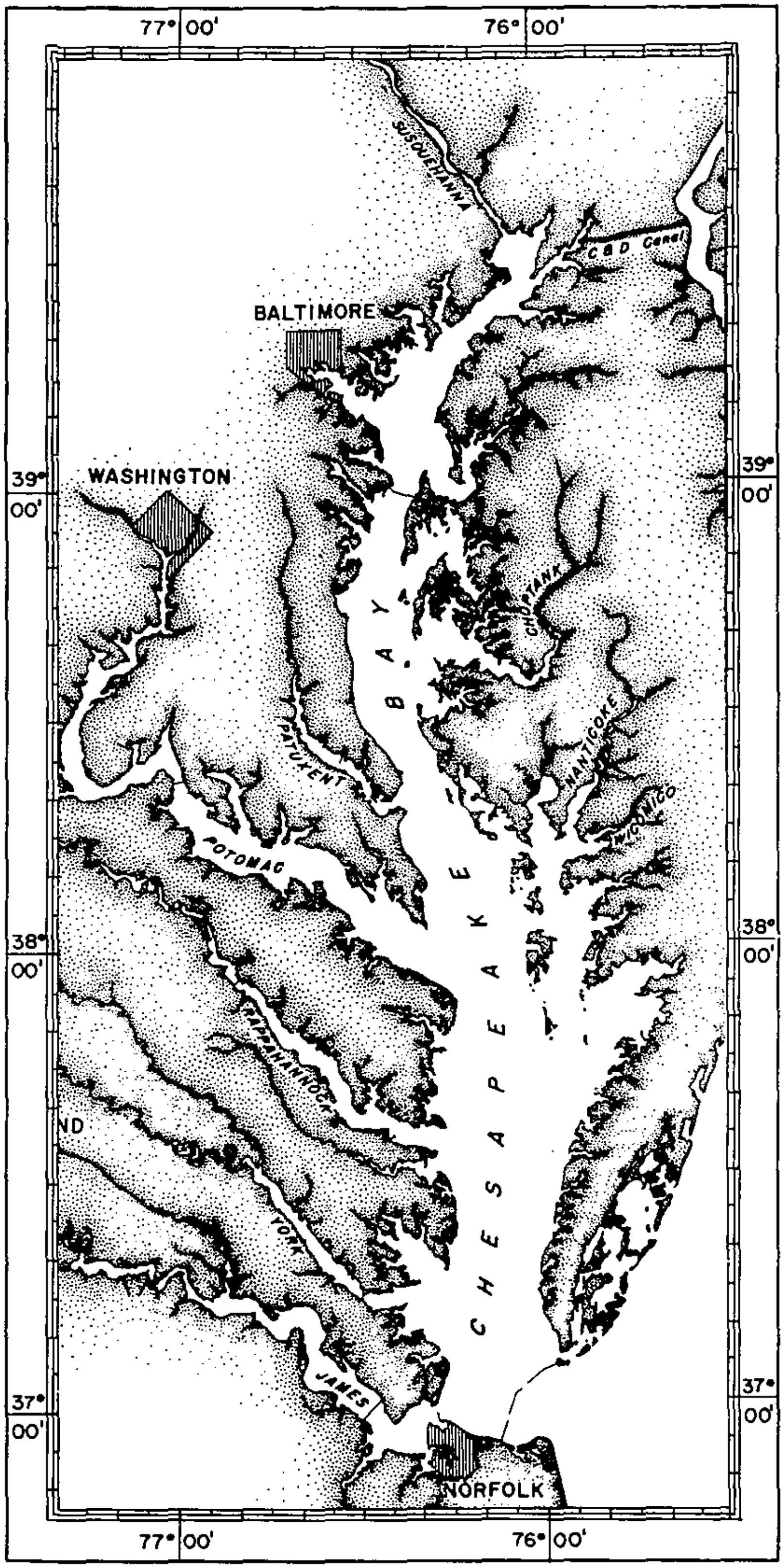


Figure 1. Map of Chesapeake Bay. (Courtesy of Chesapeake Research Consortium, Inc.)

2. HISTORICAL ICING ON CHESAPEAKE BAY

2.1 Extreme ice conditions in the Bay

From 1604 through the early part of the nineteenth century, years having unusually cold winters in the eastern U. S., including those with severe ice conditions on Chesapeake Bay, were noted in various existing records (Ludlum, 1966). Starting in the mid-nineteenth century, meteorological record-keeping provided more complete information on ice on Chesapeake Bay. Since 1888, the following winters had cold periods sufficiently long or intense to produce more than the usual amount of ice in the Bay: 1892-93, 1894-95, 1898-99, 1903-04, 1904-05, 1911-12, 1917-18, 1933-34, 1935-36, 1939-40, 1960-61, 1962-63, and 1969-70.

In the last 25 years, satellites have made it readily possible to obtain synoptic ice data, providing much more information on annual variations in the extent of ice in the Bay. Foster (1980, 1982) discusses ice conditions on Chesapeake Bay for the winters of 1976-77 through 1980-81, noting the anomalously cold winters during this period. Ice conditions during winter 1976-77 were very severe, affecting shipping, safety, facilities, and biota in the Bay. In a normal winter, about ten percent of the Bay freezes over. However, in winter 1976-77, Foster (1980) estimated 85 percent of the Bay was covered by ice. He further noted that ice coverage of comparable magnitude occurred in one other winter, 1917-18, determined from available ice records and a similarity in fall and winter air temperatures for 1917-18 and 1976-77.

2.2 Effects of ice cover on Bay economy and biota

Ice in the Chesapeake Bay area affects water-related activities and certain biological resources in some years, depending on the severity and duration of ice cover. Waterborne commerce on large ships such as those bearing containerized cargo is usually affected only in years with severe ice conditions. The primary route used by large, ocean-going commercial ships is in the Bay mainstem, which stays relatively free of ice in all but the most severe winters. In severe ice years such as winter 1981-82, container vessels scheduled to travel through the Chesapeake and Delaware Canal, where draft restrictions may be imposed when navigation of the canal becomes hazardous, are sometimes re-routed through Norfolk, VA. Ice is more of a problem to smaller vessels in rivers and tributaries such as on the Eastern Shore, where ice cover can hamper the movement of energy supplies being delivered via the Nanticoke and Wicomico Rivers.

Icing can damage various structures on the Bay including navigational aids and docks. During winter 1983-84, ice caused $200,000 damage to navigational aids in the middle and upper Bay and caused extensive damage to recreational fishing piers at Hart Island, MD, (Dowgiallo et al., 1984). Wooden-hull boats and anchor-gill nets used by watermen are also susceptible to damage from ice as occurred in winter 1983-84. Watermen, particularly oystermen, in some winters have lost significant amounts of harvest time due to ice covering harvest areas.

Ice cover affects the winter feeding of migratory waterfowl on brackish water plants. Lovvorn (1988) found that ice cover in some winters from 1956-87 made certain plant-tuber foods inaccessible to feeding by canvasback ducks (Aythya valisineria) during parts of January and February. Although both the aquatic plants on which the canvasbacks feed and the ducks themselves have shown a historical decline in Chesapeake Bay, ice cover was also perceived as having influenced food availability and possibly, canvasback distributions in some winters in the mid-Atlantic region.

Unusually cold water temperatures in some winters cause mortalities of certain finfish species such as croaker (Micropogonias undulatus), which over-winter in Chesapeake Bay (Norcross, 1983). A rapid drop in water temperature below the croaker tolerance limit of 4 $^{\circ}C$ can result in the loss of most, or all, of a year class. In extremely cold years, mortalities of other species may occur. Foster (1980) reported oyster (Crassostrea virginica) and blue crab (Callinectes sapidus) mortalities in the upper Bay during winter 1976-77, when a large portion of the Bay was covered with ice.

3. METHODS AND MATERIALS

To detect and evaluate the surface area covered by ice on Chesapeake Bay with satellite imagery, the approximate date of maximum coverage was first identified using a combined analysis of air and water temperatures, freezing degree-days, and U. S. Coast Guard ice reports. This analysis also provides information on the duration of ice cover by observing the timing of the coldest water temperatures and by estimating ice thickness as a function of time using freezing degree-days. The methods used in these analyses are described here.

3.1 Air and water temperatures

Cooling and freezing periods in fall and winter can be seen by monitoring air and water temperatures for selected stations in the Chesapeake Bay area. Average daily air temperatures for the winter freeze period of December through February were obtained from the National Weather Service's weather station at Baltimore-Washington International (BWI) airport. In this area of the Bay, BWI is the closest station to the Bay mainstem that has average daily air temperature available. The BWI station represents temperature conditions over a wide area of the upper Bay.

Surface water temperatures were provided by the National Ocean Service for the station at Annapolis, MD. Daily data were available from this station except for some weekends and holidays. To show the relationship between them, air and water temperatures were compared for Annapolis for December through February (Figure 2, Section 4), as air temperature data were also available. The air temperature data from Annapolis are single daily measurements. All data were loaded onto and analyzed on a personal computer.

3.2 Freezing degree-days

Using the Fahrenheit (F) temperature scale, a freezing degree-day (FDD) is defined as the positive difference between 32 ^{o}F and the daily average air temperature. For example, an average air temperature of 25 ^{o}F gives 7 FDDs (32 ^{o}F - 25 ^{o}F = 7 FDDs). Air temperatures of 32 ^{o}F and higher produce zero FDDs as melting will occur.

Daily accumulations of FDDs may be summed to show the amount of cooling for a series of days. Daily, monthly, and seasonal accumulations of FDDs have been used to show the relationship between air temperature and ice formation in studies in Chesapeake Bay (Foster, 1980) and in cooler regions such as the Great Lakes and Canada (Assel et al., 1983). In the present study, the relationship between air temperature and FDDs is shown by comparing the daily average air temperature and the daily totals of FDDs for December through February (Figure 3, Section 4).

The accumulation of FDDs may be presented cumulatively by adding only positive FDDs or by totalling both positive and negative FDDs to allow for melting. For a succession of days throughout the winter, the latter procedure usually produces a marked peak which can be used to identify the approximate day of maximum ice cover (Figure 4, Section 4). This method has been applied in other studies of ice formation in the Great Lakes (Assel et al., 1983) and Chesapeake Bay (Foster, 1980). A description of the method of using negative values of FDDs to reduce accumulated totals is described by Boyd (1975).

Ice thickness can be estimated for a given location using the accumulated FDDs in a modification of Stefan's formula (Neumann and Pierson, 1966):

$$\text{Ice Thickness} = k\sqrt{(2K_i/\rho_i L_i)\text{Accumulated FDDs}}\ ,$$

where K_i is the coefficient of thermal conductivity of ice, ρ_i is the density of ice, and L_i is the latent heat of fusion. When ice thickness is expressed in inches and FDDs are in ^{o}F the lumped coefficient (in parentheses inside the radical) has a value near unity. The coefficient k before the radical has been found to range from 0.3 to 0.8 to account for differences between air temperatures and ice surface temperatures and other sources of inefficiency in the heat transfer process (Neumann and Pierson, 1966). Assigning k = 0.4 adequately represented the observed thickness during ice buildup for upper Chesapeake Bay for winter 1987-88 (Figure 5, Section 4).

Ice formation in protected areas of the upper Bay probably is better represented by the thickness computed from the formula, whereas open water areas subject to winds, tides, and currents may not closely follow the predicted curve. Observed ice thickness values were extracted from U. S. Coast Guard ice reconnaissance reports for the upper Bay covering the 1987-88 ice season.

3.3 Satellite image analysis for Chesapeake Bay ice cover

To examine ice cover on Chesapeake Bay, imagery was used from two types of satellite data: Multispectral Scanner (MSS) data from Landsat and Advanced Very High Resolution Radiometer (AVHRR) data from the NOAA TIROS-N series of polar-orbiting satellites. Dates for the imagery covering the 1987-88 ice period were selected based on a combined analysis of freezing degree-days, water temperatures, and U.S. Coast Guard ice reports.

Ice cover in winter 1987-88 was near normal (Section 4.4). To compare this near-normal winter with a relatively severe year for ice, AVHRR imagery was also acquired for winter 1981-82. Landsat and AVHRR imagery were searched for relatively cloud-free days on or near the dates of peak ice cover for both the 1981-82 and 1987-88 winters.

Landsat passes over the upper Bay near the dates of peak ice cover in 1982 and 1988 were viewed on microfiche at the Earth Observation Satellite Company (EOSAT) in Lanham, MD. Landsat imagery selected for study was analyzed using an MSS band 2 photographic print centered on Washington, D.C. This print covers much of the middle and upper Chesapeake Bay and tributaries. Resolution of the Landsat MSS data is 80 m. Higher resolution (30 m) Landsat Thematic Mapper (TM) imagery was also available but was not used, since in the Chesapeake Bay and tributaries the 80 m resolution clearly shows the ice. Ice cover in the Landsat scene was interpreted visually directly from the photographic print.

Facsimile prints of AVHRR scenes for the peak ice dates were viewed in the photo archives of the National Environmental Satellite, Data, and Information Service in Camp Springs, MD. Relatively cloud-free scenes were selected based on the examination of thermal and visible imagery. Data were requested for the area from 34 to 42 degrees North latitude. Data were obtained on magnetic tape for both scenes and processed using the VAX system 11/780 software developed at the Assessment and Information Services Center and the EASI/PACE image processing software package (developed by PCI, Inc.) on a personal computer. The data were mapped to a Mercator projection. At 38 degrees North latitude, or mid-Chesapeake Bay, the Mercator projection has a pixel size of 1.18 km. At 37 degrees North latitude near the mouth of the Bay, resolution is 1.19 km; at 39.5 degrees North latitude in the upper Bay, resolution is 1.16 km.

The visible channel 1 AVHRR data were used to delineate ice in Chesapeake Bay according to the technique described by Everdale (1985). Using this technique, reflectance of 8 percent and above in the imagery is used to delineate snow and ice cover. Snow and ice have higher reflectance values than water or bare land due to the highly reflective surface of the snow and ice. Water areas free of ice appear dark, i.e., they have relatively low reflectances, as is normally observed for water, while areas of snow and ice cover will be bright. The land in each AVHRR scene was masked using an overlay generated from World Data Base geography data to separate snow-covered land from water. A computer program for geographic correction was used to align the

Chesapeake Bay shoreline in the satellite images with the geography of the Bay in the land mask.

To permit a more quantitative comparison of the different scenes, the surface reflectance for channel 1 was determined. Converting the radiance data to reflectances corrects for most atmospheric contamination and sun angle effects, thereby allowing comparisons of one scene to another. The computation used the procedure presented by Stumpf (1987) for determining the reflectance from water using a simple correction for the atmospheric path radiance and the solar zenith angle.

Reflectance (R) was calculated as follows:

$$R = \frac{\pi\ (L_* - L_A)}{E_o \cos \theta_o},$$

where L_* is the radiance measured at the satellite, L_A is the atmospheric path radiance, E_o is the solar irradiance, and θ_o is the solar zenith angle (when the sun is directly overhead the angle is 0^o; when it is at the horizon the angle is 90^o). L_A is estimated in a clear water region (Stumpf, 1987) and, here, assumed constant over the Bay.

A value of 1.0 for R means 100 percent reflectance; a value of 0 corresponds to complete absorption of the incident solar irradiance. The calculation of reflectance permits direct comparisons of the ice brightness for scenes taken at different times, at different latitudes, or with different sensors (e.g., Landsat MSS band 2 would produce approximately the same reflectance as AVHRR channel 1).

3.4 Use of Geographical Information System to display ice coverage

The ice cover in the satellite imagery was compared to the U. S. Coast Guard observations of the types of ice present in areas of the upper Bay. Ice reports are issued daily by the U.S. Coast Guard from observations made during shipboard ice reconnaissance on Chesapeake Bay. Ice-coverage was extracted from U. S. Coast Guard ice reconnaissance teletype reports for the day of maximum ice coverage and visually displayed using a Geographical Information System (GIS).

To easily relate the AVHRR satellite scenes to the Coast Guard observations using the GIS, the same geography (World Data Base map data) used to mask the land in the satellite scenes was used as a base map to display the ice observations. Each ice type was digitized in the appropriate location of the Bay geography in a separate image plane or overlay. The ice types in the individual image planes could then be color coded and overlaid directly onto the map of the Bay. The map and ice coverage were saved as an image for comparison to the satellite imagery.

U. S. Coast Guard ice reports are provided in hardcopy teletype form, covering standard observation areas along with ice thickness (in inches), for example: Howell Point to Worton Point, 4-6 inches close pack, and Choptank River entrance, no ice.

Ice concentration is reported using the following terms:

(a) OPEN WATER: less than 1/8 coverage
(b) VERY OPEN PACK: 1/8 to 2/8 coverage
(c) OPEN PACK: 3/8 to 5/8 coverage
(d) CLOSE PACK: 6/8 coverage
(e) VERY CLOSE PACK: 7/8 coverage
(f) COMPACT PACK: 8/8 coverage - complete

The U. S. Coast Guard occasionally supplements the six types of ice coverage with additional descriptions, depending on ice conditions on the Bay. "New ice" is a general term for recently formed ice that includes frazil ice, grease ice, and slush. These types of ice are composed of ice crystals that are weakly frozen together (if at all) and have a definite form while they are afloat. "Fast ice" is sea ice which forms and remains fast, where it is attached to the shore, or between shoals. Fast ice may be formed in place from sea water or by the freezing of pack ice to the shore. "Pack ice" is a term used in a wide sense to include any accumulation of sea ice other than fast ice, no matter what form it takes or how disposed. During severe ice conditions on the Bay, "rafting," caused by pieces of ice overriding one another, and "ridging," caused by multiple pieces of ice rafting, can occur.

4. RESULTS

4.1 Weather and oceanographic summary and analysis for 1987-88

Daily air and surface water temperatures for the National Ocean Service station at Annapolis, MD, covering December 1987 through February 1988 are shown in Figure 2. Air temperatures remained above freezing for most of December, and water temperatures dropped slightly. In January, air temperatures dipped well below freezing through mid-month, followed by a sharp decline in water temperatures, which reached freezing on the 14th and 15th of the month. Following this, air temperatures were mostly above freezing for the remainder of the winter, and water temperatures stayed above freezing.

The below-freezing periods can be seen more clearly in the daily totals of freezing degree-days (FDDs) for December 1987 - February 1988, computed from average daily air temperatures at BWI Airport (Figure 3). The highest number of FDDs are seen during the first half of January, followed by three short periods of daily accumulations in late January and the first half of February.

Figure 4 shows accumulated FDDs over the 1987-88 ice season. When temperatures rose above freezing, the departures from freezing were subtracted from the cumulative total. The number of FDD's peaked on January 16, afterwards showing a decline, which reflects above-freezing air temperatures. The peak on January 16 marks the date of maximum ice cover on the Bay for the 1987-88 winter, in close agreement with U. S. Coast Guard observations on the upper Bay. After January 16, melting began, and the ice accumulated in the Bay had not reached sufficient mass or strength to persist through the winter. Further brief intrusions of below-freezing air temperatures were not cold or long enough to result in continued accumulation of ice.

4.2 Model of computed versus actual 1987-88 ice cover

Figure 5 shows 1987-88 ice thickness in the upper Bay as the modeled amount, computed using a modification of Stefan's formula (Section 3.2), and the observed amount from U. S. Coast Guard ice observations in the area from Worton Point to Swan Point. Large ship traffic and wind have an important effect on ice cover in this area of the upper Bay. Thus, reported thicknesses sometimes show large daily variations, accounting for the relatively low thicknesses reported for this area around January 16, the estimated date of peak ice cover. The modeled ice thickness curve follows the observed thickness plot fairly well during ice buildup until near the date of maximum ice cover on January 16. Afterwards, the modeled thickness does not drop as

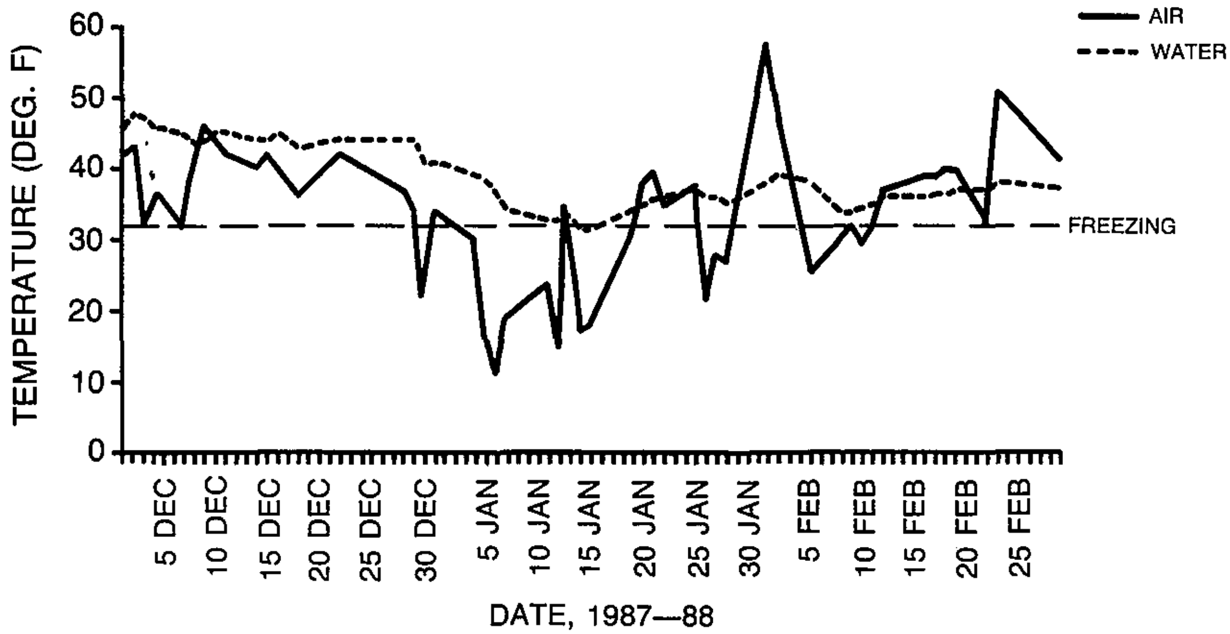


Figure 2. Daily air and surface water temperatures, Annapolis, MD, December 1987 - February 1988. Data from NOAA, National Ocean Service.

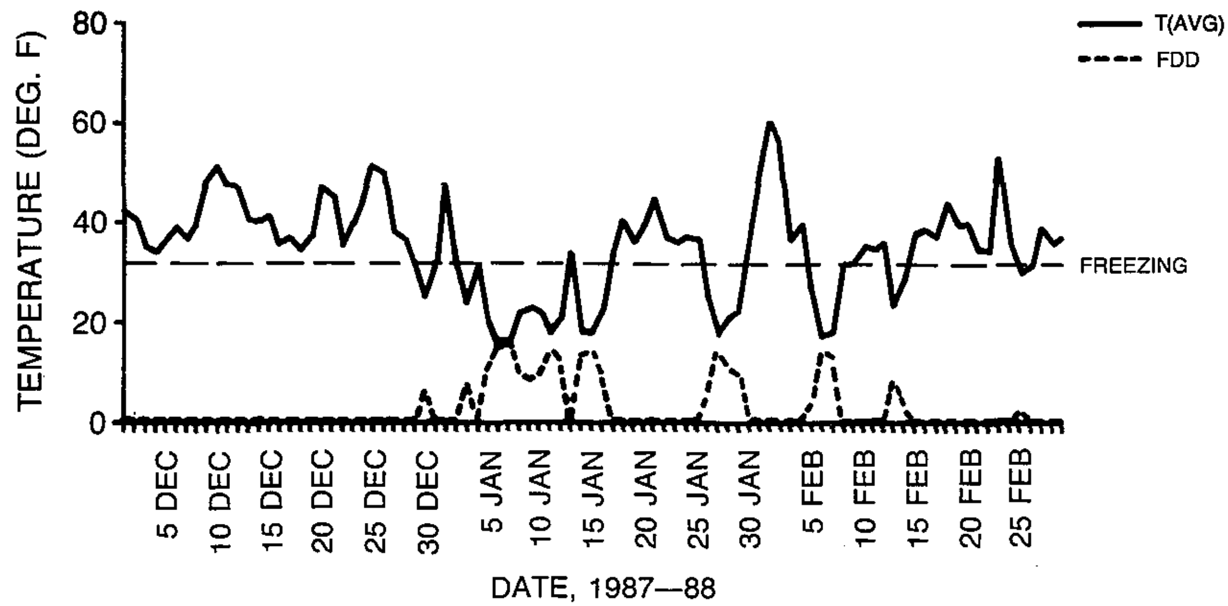


Figure 3. Daily air temperatures and freezing degree-days, Baltimore-Washington International Airport, December 1987 - February 1988. Data from NOAA, National Weather Service.

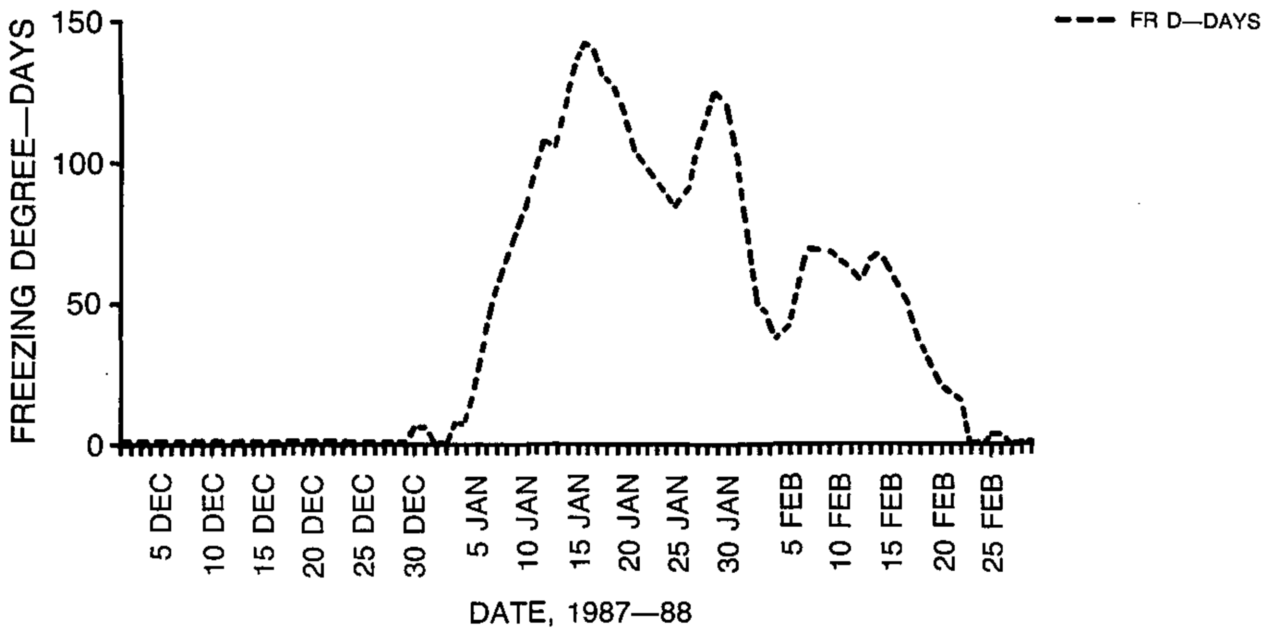


Figure 4. Freezing degree-days accumulated at Baltimore-Washington International Airport, December 1987 - February 1988. Data from NOAA, National Weather Service.

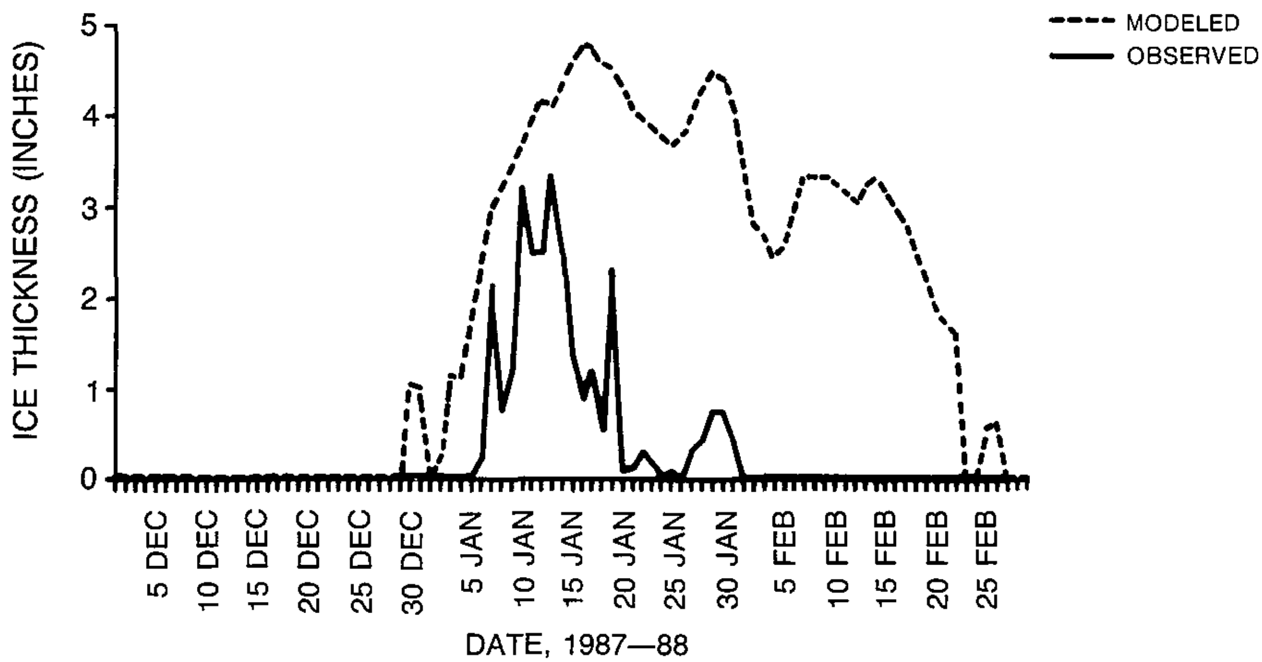


Figure 5. Modeled versus observed daily ice thickness for the winter 1987-88 ice season. Modeled thicknesses were computed from freezing degree-day accumulations at Baltimore. Ice observations were taken from U. S. Coast Guard ice report messages for the upper Bay.

quickly as the observed thickness does. This occurs because the computation for the modeled thickness considers only air temperatures and does not account for the complex forces which influence ice breakup such as wind and hydrographic conditions.

4.3 Satellite imagery, winter 1987-88 and 1981-82

Landsat MSS and AVHRR scenes were obtained for the available relatively cloud-free days as near as possible to the date of peak ice cover for the 1987-88 winter, January 16, 1988. AVHRR scenes are available daily, and a cloud-free scene was selected for January 16. A cloud-free Landsat scene was selected for January 11, 1988, the closest Landsat pass date, which are every 16 days, near the peak ice cover on January 16, 1988 (Figure 6).

For comparison to a colder winter with more ice, available imagery was also obtained for the date of maximum ice cover during the 1981-82 winter, January 27 (NOAA, 1982). A nearly cloud-free AVHRR scene was available for January 26, 1982. A relatively cloud-free Landsat scene was not available on or near January 27, 1982.

Landsat MSS imagery

The Landsat scene shows ice cover in most of the embayments on the western shore above the Patapsco River. Ice in this area appears consolidated and fixed to the shoreline. Ice in the upper Bay mainstem appears loosely consolidated and broken, probably from the effects of wind, tides, and currents in the relatively open and deeper water. The freezing degree-day analysis (Sections 4.1 and 4.2) shows that freezing conditions occurred until January 16. Since the image in Figure 6 was taken on January 11, it is likely that more ice formed later, especially in the upper Bay mainstem. Many of the smaller tributaries and marshes along the Eastern Shore are ice covered in the January 11 scene. Approaches to the main rivers on the Eastern Shore show evidence of ice accumulations. Loose and broken ice can be seen in parts of the middle and upper Potomac River. The bright white areas in the upper Potomac (Occoquan Bay) and the upper Bay Western Shore are probably snow-covered ice.

AVHRR imagery

Relatively cloud-free scenes were available from the NOAA-7 and NOAA-10 satellites, respectively, for January 26, 1982 and January 16, 1988 (Figure 7). Ice in the 1988 scene appears well-formed along much of the Bay shoreline and has consolidated over the upper reaches of the Bay mainstem. There is a considerable amount of ice cover in the rivers and marshes of the eastern shore. Most of the Bay mainstem and lower portions of rivers on

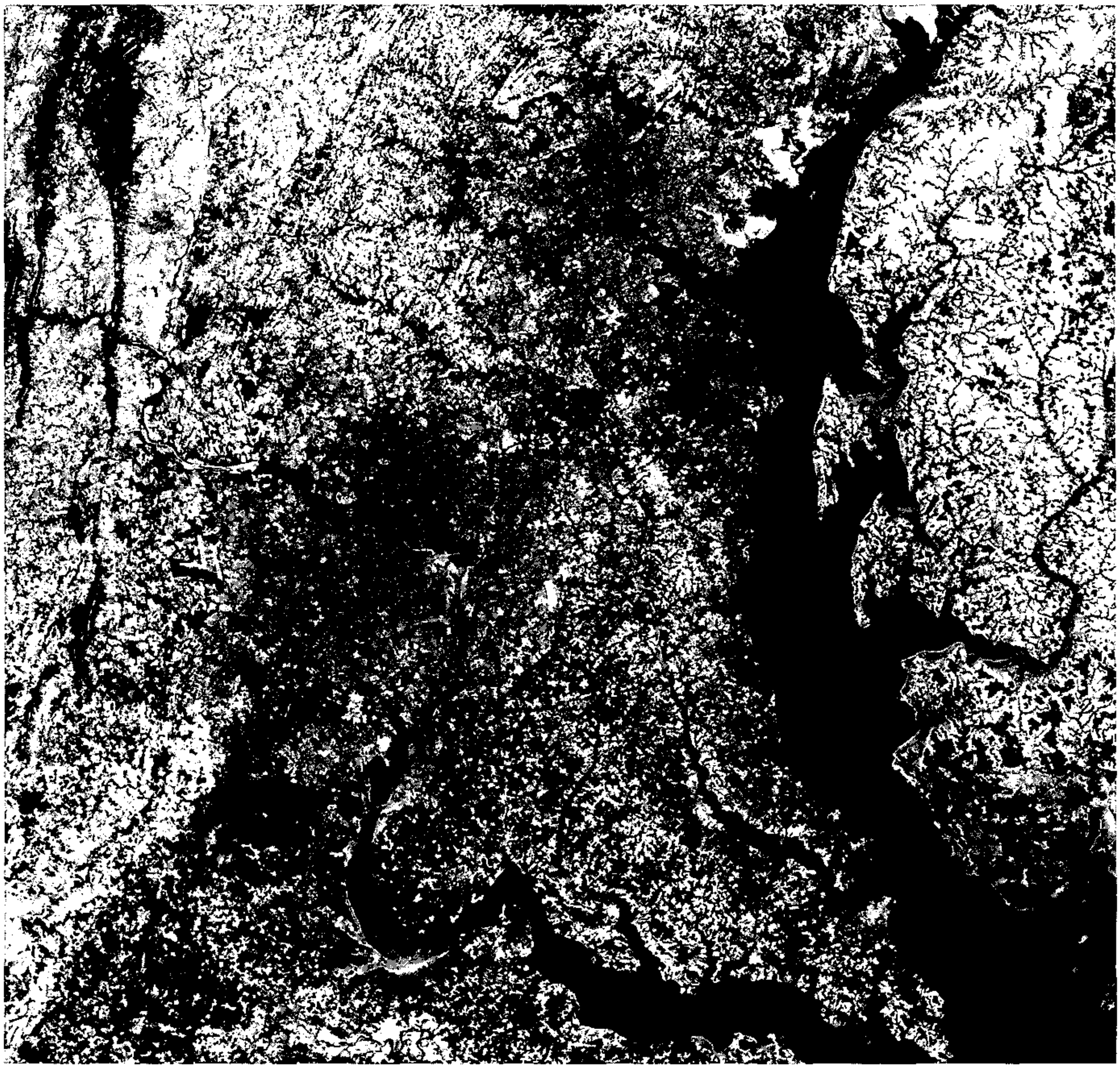


Figure 6. Northern half of Chesapeake Bay from Landsat satellite, MSS band 2, January 11, 1988. (Reproduced by permission of EOSAT.)

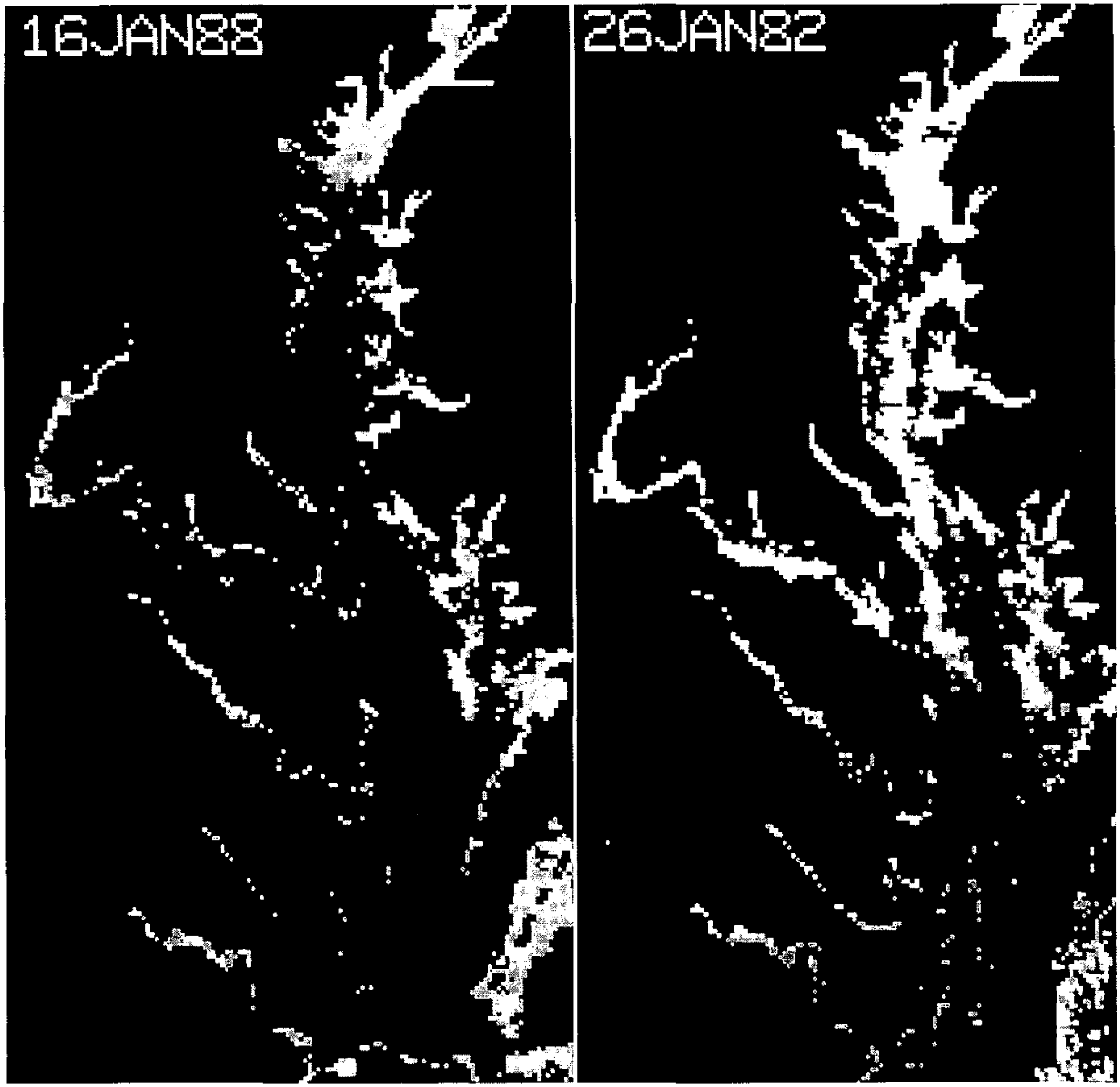


Figure 7. Chesapeake Bay ice cover on January 16, 1988 and January 26, 1982 from NOAA-10 and NOAA-7 satellites, respectively. Both scenes are AVHRR channel 1 data, digitally enhanced to distinguish ice from water. Land areas are masked to separate land from water. Clouds inside the lower Bay in the January 26, 1982 scene are masked.

the Western Shore appear ice free.

Much more ice is seen in the open-water areas in the January 26, 1982 scene. Most of the upper reaches of the Bay mainstem appear ice covered as are rivers and marshes of the Eastern Shore. A thin channel of open water was evident along the north shore of the Patapsco River (approach into the Baltimore Harbor area) during processing of the 1982 scene, though it is not detectable in the photograph. The jagged features of the ice in the relatively large area of the Bay mainstem just above the center of the scene are probably drifting ice floes. Potomac River ice is well formed along the southern shoreline with open water along the north shoreline from mid-river to the mouth.

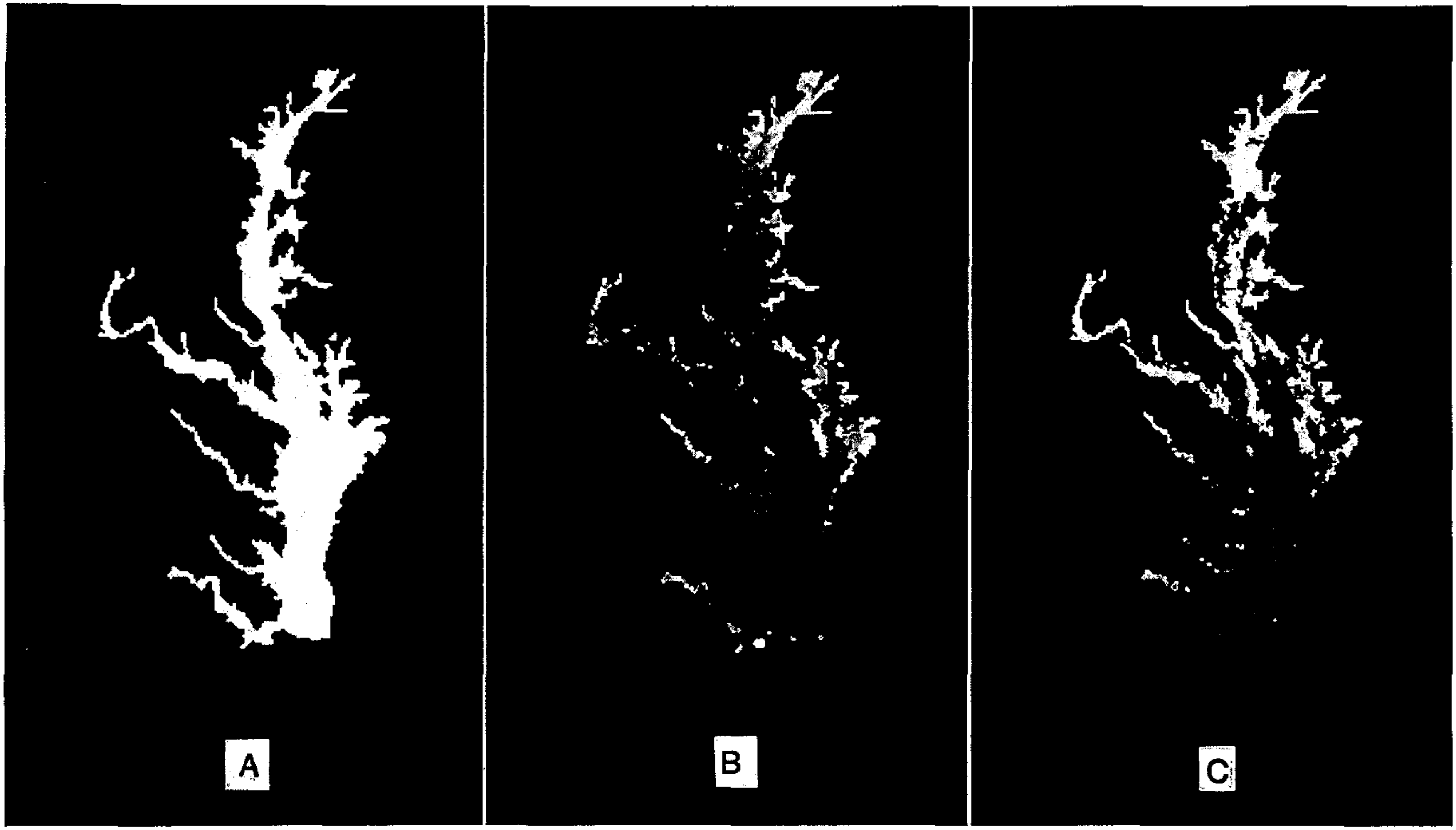
4.4 Percent maximum ice cover, winter 1987-88 and 1981-82

Percent ice cover was determined for the peak ice coverage dates (January 16, 1988 and January 26, 1982) by analysis of the digital AVHRR data. Figure 8A shows the area of the Bay used in the analysis along with the peak ice cover in the winters of 1987-88 (Figure 8B) and 1981-82 (Figure 8C). The total number of picture elements (pixels) plotted for the Bay area in Figure 8A was 6,474. Solid or consolidated ice areas appeared to have a reflectance of greater than 8 percent in the two ice scenes. Reflectances between 5.1 to 8 percent (medium gray in the image) were considered loosely consolidated ice or the transition area between open water and ice.

Using 8 percent reflectance as the minimum value for ice, 14 percent of the pixels in the January 16, 1988 image showed ice cover. In the January 26, 1982 image, 34 percent showed a reflectance greater than 8 percent. Peak ice cover of 14 percent during the winter of 1987-88 was near normal, when compared to the 10 percent coverage Foster (1982) reported as normal for Chesapeake Bay.

Differences in methodologies in deriving percent ice coverage (i.e., using a planimeter to trace the ice outline from an image versus digital analysis) probably will show somewhat different estimates for a given year. The relative change from year to year can be determined with the planimetric method, though the digital analysis provides an objective approach that is less subject to differences in interpretation between analysts. Analysis of the digital data provides a standard method using a consistent area that can be performed at the same time the ice image is being processed.

Since Landsat MSS band 2 would produce approximately the same reflectance as AVHRR channel 1 (Section 3.3), the digital analysis presented here can be used with either Landsat or AVHRR imagery, using 8 percent reflectance as the minimum



Total bay area | 14% Ice cover | 34% Ice cover

Figure 8. (A) Total area of Chesapeake Bay used for ice analysis (100 percent), (B) 14 percent ice cover on January 16, 1988 from NOAA-10 AVHRR satellite data, and (C) 34 percent ice cover on January 26, 1982 from NOAA-7 AVHRR satellite data. Images B and C were processed to show ice only. Reflectances of less than 5 percent (including open water) appear black. Clouds in the lower Bay in the January 26, 1982 scene were masked.

value for ice.

The resolution of the AVHRR data at mid-Chesapeake Bay (38 degrees N) is 1.18 km. Since one pixel represents 1.39 km^2 (1.18 km X 1.18 km), the area considered for ice analysis in Figure 8A covers 6,474 pixels, or 9,014 km^2 (3,480 mi^2). Cronin (1971) reported the total surface area of the Bay mainstem to be about 6,500 km^2 (2,500 mi^2) and the total estuarine system, including tributaries, to be about 11,500 km^2 (4,400 mi^2). The area used for ice analysis in the present study is less than Cronin's estimate for the total area of the Bay. The difference is due mainly to the resolution used in the satellite image processing, which, generally, makes it difficult to include geographical features less than about 2 km. A substantial portion of the dendritic-like uppermost portions of rivers and creeks feeding into the Bay and small embayments are thus not completely included in the pixel-count estimate of the Bay's total estuarine system.

The area of the Bay mainstem, excluding major tributaries, in Figure 8A and Cronin's (1971) estimate for approximately the same area are closer than in the comparison between the total surface area for the entire Bay system given by the two methods. The difference in area between the two estimates for the Bay mainstem is due in part to the loss of shoreline from the geography's overlapping part of the water in Figure 8A and from not including small embayments along the shoreline.

4.5 U. S. Coast Guard ice reconnaissance

The areal coverage of ice seen in the Landsat and NOAA TIROS-N satellite images was supplemented with U. S. Coast Guard shipboard observations that provide information on ice type and thickness for various locations in Chesapeake Bay. Ice coverage on upper Chesapeake Bay and the Potomac River on January 16, 1988, the estimated date of maximum ice cover for winter 1987-88, is shown in Figure 9.

Six types of ice coverage reported by the Coast Guard are coded in the color scale in Figure 9 (Section 3.4). Compact pack ice is seen in areas along the upper Bay Western Shore and in some rivers on the Eastern Shore. Thicknesses of the compact pack ice ranged from four to six inches. Very close pack ice occurred in the upper reaches of the Bay mainstem and the northern part of the Chester River mouth with thicknesses of four to six inches. Some ridging occurred in the very close pack ice in the upper Bay mainstem.

New close pack ice, two to four inches thick, was observed in the upper Bay mainstem, and new close pack ice of one inch thickness was found in the Bay mainstem opposite the Patapsco

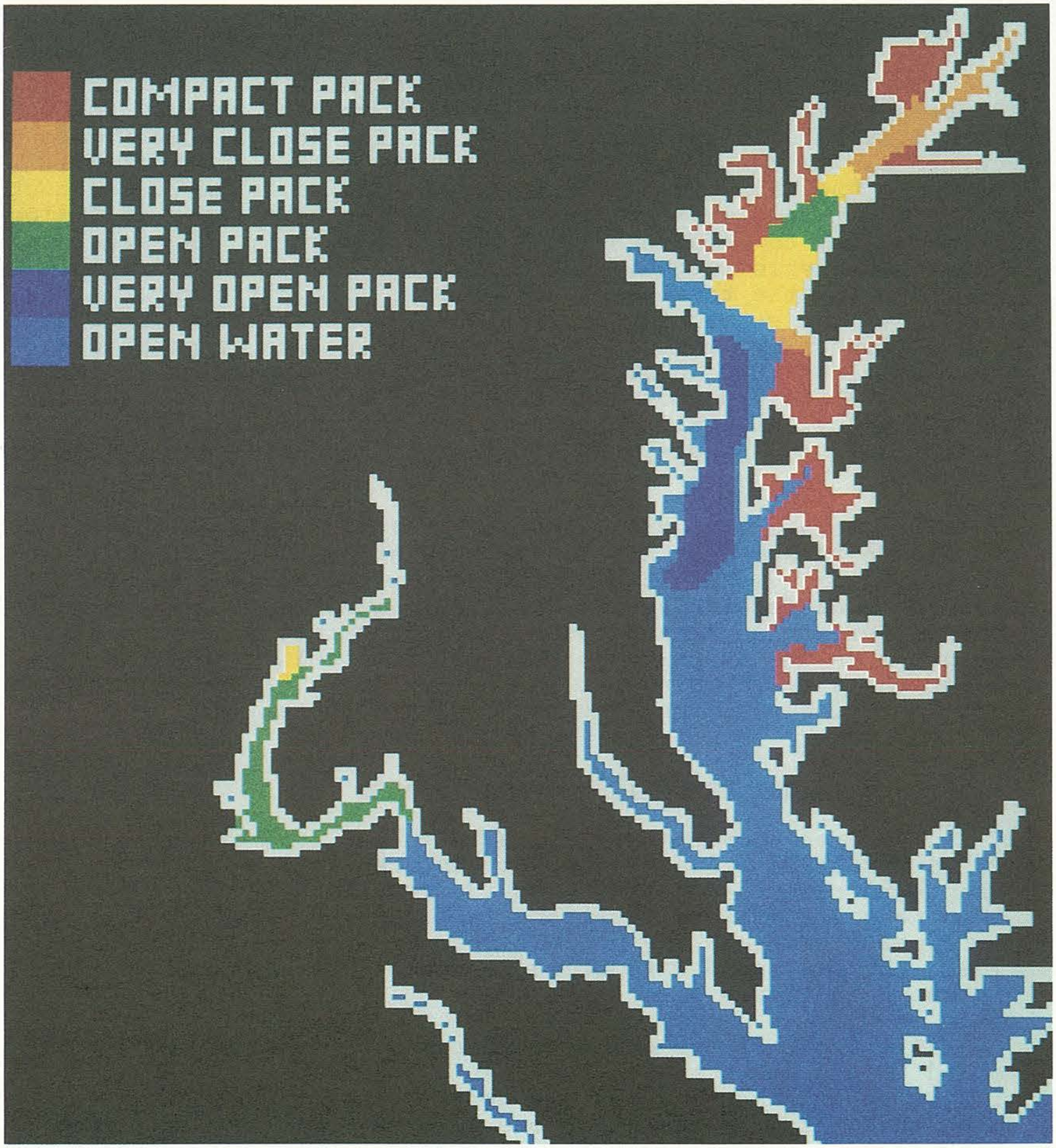


Figure 9. Ice coverage on upper Chesapeake Bay and Potomac River on January 16, 1988 from U. S. Coast Guard ice reconnaissance. No data were digitized for the middle and lower Bay areas. Ice type and location were taken from U. S. Coast Guard ice report messages and digitized onto the Chesapeake Bay geography.

River. Close pack ice, two to four inches thick, occurred in Occoquan Bay in the Potomac River. New open pack ice, one to three inches thick, was reported in the upper Bay off the Tolchester Beach area. Open pack ice ranging from one to five inches was reported over a large area of the middle and upper Potomac River. Very open pack ice, one to three inches thick, was reported over a relatively large area starting just above the Bay Bridge. From additional Coast Guard reports of open water in this same area, apparently this ice appeared intermittently over the area shown in Figure 9.

5. SUMMARY AND CONCLUSIONS

5.1 Summary of observations

Daily totals of freezing degree-days accumulated over the 1987-88 ice season on Chesapeake Bay indicate that the date of maximum ice cover was January 16, 1988. During ice buildup, the computed daily ice thickness follows the observed ice thickness. Afterwards, the computed ice thickness does not follow the observed thickness, because the computed thickness does not account for ice breakup. Maximum ice cover of 14 percent during winter 1987-88 was near normal for the Bay area. Maximum ice cover in a more severe year, winter 1981-82, was estimated at 34 percent. U. S. Coast Guard ice reconnaissance on the upper Bay showed that six ice-coverage types were present during winter 1987-88, with thicknesses up to six inches.

5.2 Relative merits of various satellite imagery types

Ice cover on Chesapeake Bay can be detected and evaluated using AVHRR satellite data and a land mask. The higher-resolution Landsat imagery provides a detailed view of ice cover permitting clear delineation of certain ice features. However, the higher frequency of passes of the polar-orbiting satellites produces more AVHRR scenes through the ice season. Daily monitoring of ice is possible with AVHRR data, which is available near-real-time, limited only by cloud cover.

5.3 Possible applications of methodologies

AVHRR data can be used, along with the temperature, freezing degree-day, and ice thickness analyses, in an integrated study of ice cover on Chesapeake Bay. The digital analysis technique permits rapid and effective estimates of percent ice cover. The date of maximum ice cover can be determined and compared from year to year. These techniques, in combination with available Landsat imagery for study of fine-scale features, can measure the severity of ice conditions during a given winter, which can then be related to effects on the Bay environment and economy.

5.4 Recommendations for further study

The present study demonstrates that AVHRR data can be used to detect and evaluate ice cover on Chesapeake Bay. The percent estimates of ice coverage will be more useful once it is determined how precise these estimates are. One approach is to follow the growth and the decay of ice on the Bay for an entire winter season with daily AVHRR data, along with accumulated freezing degree-days computed from air temperatures from several stations around the Bay. Tracking ice growth and decay from a series of AVHRR scenes will provide a better understanding of the precision with which ice can be detected in an individual scene, further separating out interference that can be caused by cloud cover, haze, and, possibly, turbidity. Once this is accomplished, AVHRR data can be more accurately compared year to year, possibly with multiple-year averages, leading to an ice climatology for Chesapeake Bay.

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NESDIS TECHNICAL MEMORANDA

(continued from inside of front cover)

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